Abnormal Frontal Plane Knee Mechanics During Sidestep Cutting in Female Soccer Athletes After Anterior Cruciate Ligament Reconstruction and Return to Sport

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**Background:** Athletes who have undergone anterior cruciate ligament reconstruction (ACLR) have a high risk of reinjury upon the return to sports participation. While the mechanisms behind this increased risk of reinjury are unknown, it has been suggested that altered knee biomechanics during sports-specific activities may be a contributing factor.

**Purpose/Hypothesis:** To compare frontal plane knee joint angles and moments during a sidestep cutting maneuver in female soccer athletes who have undergone ACLR with those in athletes with no history of knee injury. It was hypothesized that athletes with a history of ACLR would exhibit increased knee abduction angles and knee adductor moments compared with those with no history of injury.

**Study Design:** Controlled laboratory study.

**Methods:** Twelve female soccer players with a history of ACLR served as the experimental group, and 12 female soccer players with no history of knee injury constituted the control group. Three-dimensional kinematics and ground-reaction forces were collected while each participant performed a sidestep cutting maneuver. Variables of interest included the knee abduction angle and knee adductor moment during the early deceleration phase of the cutting maneuver. Independent-samples t tests were used to evaluate differences between groups (P ≤ .05).

**Results:** Participants in the ACLR group exhibited increased average knee abduction angles (ACLR: 3.8° vs control: 1.8°; P = .03) and peak knee adductor moments (ACLR: 1.33 N·m/kg vs control: 0.80 N·m/kg; P = .004) compared with the control group.

**Conclusion:** Female soccer players who have undergone ACLR and returned to sports participation exhibited increased knee abduction angles and knee adductor moments during the early deceleration phase of cutting compared with their healthy counterparts with no history of knee injury.

**Clinical Relevance:** Even though athletes are able to return to sport after ACLR, they are at an increased risk for reinjury. It may be the case that the increased frontal plane knee angles and moments exhibited by these athletes after ACLR could be contributing to this risk for reinjury. Therefore, it is important that rehabilitation programs after ACLR include the restoration of frontal plane knee mechanics.

**Keywords:** ACL reconstruction; sidestep cutting; knee; valgus

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Injury of the anterior cruciate ligament (ACL) is devastating to athletes who actively participate in sports and has potential long-term implications for knee joint health and function.19,23,29 The standard care for athletes who experience functional instability after an ACL injury is surgical reconstruction of the ligament. These reconstruction techniques involve replacement of the torn ACL with either an autograft (typically a bone–patellar tendon–bone or semimembranosus gracilis graft) or an allograft.15 After ACL reconstruction (ACLR), patients typically undergo vigorous rehabilitation for 3 to 6 months and are allowed to return to sports participation within 6 to 12 months or when their performance on specific clinical tests of lower extremity strength and agility is within 80% to 90% of the performance on their uninjured lower extremity.5,6,18
The goal of ACLR and subsequent rehabilitation is to restore anatomic and functional stability to the knee joint. This surgery is considered successful, as documented in the literature citing the restoration of sagittal plane knee stability utilizing a KT-1000 arthrometer and high patient satisfaction scores on clinical questionnaires. However, while ACLR appears to restore ligamentous stability to the knee joint and allows for a return to sports participation, recent studies have suggested that it may not be as successful as previously thought. A recent study by Ardern et al reported that up to 66% of competitive athletes were unable to return to their previous level of sports participation 1 year after ACLR. For athletes who are able to return to sports participation, 12% to 25% of those reinjure their ACL within 7 years of surgery, with the highest risk present in the first 2 years after surgery. The rate of risk for reinjury upon the return to sports participation has been reported to be as high as 1 in every 17 athletes who participate in contact sports. This rate of reinjury far surpasses the risk of initial ACL injury, where rates for even the highest risk groups are closer to 1 in every 60 to 100 athletes. In addition, younger athletes (<18 years of age) are at a higher risk of reinjury, as many return to higher levels of aggressive competition and are more likely to be performing maneuvers known to be associated with an increased risk for ACL injury (ie, landing, cutting).

Given the increased risk for reinjury upon the return to sports participation, recent studies have investigated lower extremity biomechanics during sports-specific maneuvers in athletes after ACLR. Findings from these studies indicate alterations in lower extremity biomechanics in participants up to 2 years after ACLR compared with healthy controls. While a number of studies have reported on frontal plane biomechanics in participants who have undergone ACLR and returned to sports participation, the majority of these studies have focused on biomechanical differences during landing. Frontal plane knee biomechanics are of particular interest, as increased knee abduction angles and increased internal knee adductor moments (also referred to as external valgus moments) have been found to be predictive of first-time ACL injury in a population of healthy female athletes. A study by Delahunt et al found increased knee abduction angles during a drop vertical jump in female athletes after ACLR compared with activity-matched controls. During a crossover hop, Ortiz et al reported that female patients who were at least 1 year after ACLR demonstrated increased knee adductor moments compared with healthy controls; however, no differences in knee abduction angles were reported. Initial findings reported by these studies support further investigation into frontal plane mechanics after ACLR during additional sports-specific activities.

The majority of noncontact ACL injuries have been shown to occur when an athlete is decelerating and/or changing directions. Sidestep cutting is a maneuver commonly performed during soccer and involves both deceleration and change of direction. The majority of noncontact ACL injuries observed during soccer have been reported to occur during such a sidestep cutting maneuver. Therefore, investigating frontal plane knee biomechanics in patients after ACLR during such a high-risk maneuver may be of importance in understanding the reinjury risk. It is our understanding that this is the first study to examine frontal plane knee biomechanics in this population during a sidestep cutting maneuver. The purpose of our study was to investigate frontal plane knee joint angles and moments during a sidestep cutting maneuver in soccer athletes after ACLR compared with soccer athletes with no history of knee injury. We hypothesized that female soccer players after ACLR who had returned to sport would exhibit increased knee abduction angles and adductor moments compared with athletes with no history of knee injury.

MATERIALS AND METHODS

Participants

Twenty-four female soccer players were recruited to participate in this study. Twelve female soccer players, at least 1 year after ACLR, composed the experimental group (age, 23.7 ± 1.9 years; height, 1.60 ± 0.7 m; mass, 63.6 ± 7.5 kg; time after ACLR, 46.3 ± 39.7 months). The participants had a mix of surgical graft types (allograft: n = 5; bone–patellar tendon–bone autograft: n = 3; hamstring autograft: n = 4) and were all cleared to return to full sports participation. Twelve healthy female soccer players composed the control group (age, 21.3 ± 1.2 years; height, 1.64 ± 0.5 m; mass, 63.7 ± 6.7 kg).

Control participants were excluded from the study if they met any of the following exclusion criteria: (1) previous ACL injury or reconstruction or (2) previous injury that resulted in ligamentous laxity at the ankle, hip, or knee. Participants in both the ACLR and control groups were excluded from the study if they had any medical or neurological condition that would impair their ability to perform a sidestep cutting task. Before participation, all procedures were explained, and informed consent was obtained as approved by the university institutional review board.

Instrumentation

Kinematic data were collected using a Vicon 8-camera, 3D motion analysis system (Oxford Metrics Ltd, Oxford, United Kingdom) at a sampling frequency of 250 Hz. The cameras were interfaced to a microcomputer and placed around a floor-embedded force platform (Advanced Mechanical Technologies Inc, Newton, Massachusetts). The force platform (1500 Hz) was interfaced to the same microcomputer that was used for kinematic data collection via an analog-to-digital converter. This interface allowed for synchronization of kinematic and kinetic data.

Procedures

Before kinematic and kinetic data collection, height and mass were recorded. To control for the potential influence of varying footwear, participants were fitted with the same style of cross-training shoe (New Balance Inc, Boston, Massachusetts). Reflective markers (14-mm spheres)
Three-dimensional marker coordinates during landing were reconstructed using Vicon Workstation software (Workstation, Oxford Metrics Ltd). Visual3D software (C-motion, Rockville, Maryland) was used to process the raw coordinate data and compute the segmental kinematics and kinetics for the lower extremity of interest during the sidestep cutting maneuver. Trajectory data were filtered using a fourth-order zero-lag Butterworth 12-Hz low-pass filter. The pelvis was modeled as a cylinder, and the lower extremity segments were modeled as a frustrum of cones. The local coordinate systems of the pelvis, thigh, shank, and foot were derived from the standing calibration trial. Joint kinematics were calculated using Euler angles with the following order of rotations: flexion/extension, abduction/adduction, and internal/external rotation. The frontal plane knee joint angle was defined as the orientation of the shank segment with respect to the thigh segment. Three-dimensional net joint moments were calculated using inverse dynamics equations and normalized to body mass. The joint moments referred to in this investigation are the internal resultant moments.

For the purposes of this study, only the early deceleration phase of the cutting maneuver was considered, as this is the time during which the majority of noncontact ACL injuries have been reported to occur. The stance phase was identified as the period from initial foot contact to toe-off, as determined by the force platform recordings. The early deceleration phase was then defined as the first 20% of the stance phase, as previously described. As a distinct peak in the knee abduction angle was not observed during this period, the average knee abduction angle over this phase was calculated as previously described. The peak knee valgus moment occurring during the first 20% of the stance phase was calculated as well. The peak knee valgus moment was selected, as it is commonly reported as a variable thought to contribute to the increased risk for ACL injury, and a distinct peak is observed during the first 20% of the stance phase.

**Statistical Analysis**

Independent-samples *t* tests were used to determine if there was a significant difference in the dependent variables of interest between participants in the ACLR and control groups. Statistical analyses were performed using SPSS statistical software (SPSS Inc, Chicago, Illinois). Significance levels were set at *P* ≤ .05.

**RESULTS**

The ensemble averages of the frontal plane knee angle during the stance phase for participants in the control and ACLR groups are shown in Figure 2. Female participants in the ACLR group had a significantly higher average knee abduction angle during the early deceleration phase (first 20% of stance phase) compared with those in the control group (ACLR: 3.8° ± 2.8° vs control: 1.8° ± 2.3°; *P* = .03; effect size = 0.78) (Figure 3).

The ensemble averages of the frontal plane knee moment during the stance phase for participants in the control and ACLR groups are shown in Figure 4.
Participants in the ACLR group had a significantly higher peak knee adductor moment during the early deceleration phase (first 20% of stance phase) compared with those in the control group (ACLR: 1.33 ± 0.5 N·m/kg vs control: 0.80 ± 0.4 N·m/kg; \( P = .004 \); effect size = 1.31) (Figure 5).

**DISCUSSION**

Female soccer players who had undergone ACLR and returned to sports participation demonstrated altered knee mechanics during the early deceleration phase of cutting compared with healthy controls. Studies have shown that primary ACL injury (ie, initial ACL injury as opposed to reinjury) usually occurs during the early deceleration phase of such maneuvers as cutting and landing.\(^{16,17}\)

Frontal plane biomechanical differences observed at the knee joint in our participants after ACLR may be related to an increased risk of reinjury because this occurred during the early deceleration phase of sidestep cutting.

It is well known that female athletes have a 2 to 8 times higher rate of ACL injury compared with their male counterparts.\(^1,4\) Given that the majority of these injuries (>70%) occur because of noncontact mechanisms,\(^6\) sex differences in lower extremity biomechanics have been of particular interest in explaining the disparity in injury rates. Previous studies have reported that female athletes have increased knee abduction angles and knee adductor moments during various sports-specific maneuvers. Specifically, during sidestep cutting, studies have found that female athletes demonstrate greater knee adductor moments, increased knee abduction angles, and decreased...
knee flexion angles compared with male athletes.\textsuperscript{20,21} In this study, the female soccer athletes after ACLR had increased knee abduction angles and knee adductor moments compared with healthy female soccer athletes (Figure 1). This pattern is similar to that observed in female athletes thought to be at increased risk for primary ACL injury.

The relationship between frontal plane knee loading and primary ACL injury has been supported through numerous in vivo and in vitro studies. During in vitro loading simulations of drop landings, researchers have shown that the application of an abduction load across the knee joint increased the peak normalized strain in the ACL by 30\% compared with the application of a direct vertical impulsive load.\textsuperscript{36} In vitro modeling simulations of ACL strain during a single-leg landing showed that increases in ACL strain were also observed in those with a relatively high knee adductor moment during a single-leg landing compared with those with a relatively low knee adductor moment.\textsuperscript{33}

In a prospective study, Hewett et al\textsuperscript{14} found that female collegiate athletes who went on to injure their ACL demonstrated increased knee abduction angles and knee adductor moments compared with athletes who did not suffer an injury.\textsuperscript{14} Specifically, the knee adductor moment was predictive of ACL injury, with 73\% specificity and 78\% sensitivity. Given that increased knee abduction angles and adductor moments have been shown to be predictive of primary ACL injury, findings from this study may be related to the high reinjury rate observed after ACLR and return to sport.

It is important to note that the task selected for this study was an anticipated sidestep cutting maneuver. Given that participants were able to plan for the task, performance on the anticipated sidestep cut may not be as representative of the unanticipated maneuvers typically performed during sports participation. Inclusion of an unanticipated cutting maneuver may have resulted in an even larger difference between the groups, given that athletes presented with significant differences in frontal plane knee mechanics consistent with an increased risk for ACL injury despite the ability to plan for the task. Future studies are needed to examine differences between anticipated and unanticipated maneuvers in this population.

While we observed differences in lower extremity biomechanics in female soccer players who had undergone ACLR and returned to sports participation, we do not know if these biomechanics were present before the injury or were deficits not addressed before the return to sports participation. Current guidelines for a return to sport require that the ACLR extremity be within 80\% to 90\% of the uninjured extremity during performance on specific clinical tests of strength and agility, which evaluate side-to-side differences using metrics such as maximal strength, time, and distance.\textsuperscript{5,8,13,18}

As there are a number of ways that someone may move to accomplish a particular task, these metrics may not provide enough information as to the deficits in task performance and lower extremity biomechanics that may contribute to the risk for reinjury. Maximal strength of the quadriceps and hamstrings is commonly assessed, as deficits in strength are thought to contribute to an inability to adequately stabilize the knee joint during dynamic maneuvers. However, no studies have reported a relationship between these strength measures and ACL reinjury rates. In addition, recent studies have suggested that while athletes after ACLR demonstrate $\geq$90\% muscle strength in their ACLR extremity compared with their uninjured leg, they reported poor results when rating their knee function during sports participation.\textsuperscript{20,30}

Hop tests are also commonly used to determine the readiness to return to sport, and performance is typically quantified as the distance covered or time taken to perform the task. However, there are no normative data for these tests, and normal mechanics are assumed in the uninjured extremity. A recent study by Orishimo et al\textsuperscript{24} found that while patients after ACLR could perform a single-legged hop test with a distance ratio of 93\% $\pm$ 4\% (involved/uninvolved limb), they demonstrated altered hip and knee joint biomechanics on the involved limb.\textsuperscript{24} Therefore, a major limitation of utilizing hop testing before a return to sports participation is the inability of these tests to provide information regarding lower extremity biomechanics known to be related to the risk for ACL injury.

Finally, there are no current studies linking performance on return-to-sport tests and risk for reinjury. Given the discrepancy between current guidelines for a return to sport and outcomes after return to sports participation, future studies are needed to evaluate return-to-sport criteria and reinjury risk. The altered lower extremity biomechanics observed in patients after ACLR may indicate that new return-to-sport criteria should be developed that relate to, or better capture, "at-risk" biomechanics and identify the risk for reinjury.

One limitation of the current study is that our inclusion criteria required patients to be at least 1 year after ACLR, but we did not place a limit on how many years after ACLR participants could be. Therefore, we included patients ranging from 1 year to 7 years after ACLR. Future studies of a similar size should limit their inclusion criteria to a more homogeneous group as it relates to years after ACLR, and larger studies should statistically account for years after ACLR. A second limitation is that we did not examine the contralateral limb to the ACLR limb. Future studies should include analyses of both limbs to examine potential limb asymmetries. Finally, while we suspect these athletes are at increased risk of reinjury because of their frontal plane knee mechanics, we did not follow them prospectively to determine if they incurred a reinjury. Future studies are needed to include a prospective element.

CONCLUSION

Even though athletes are able to return to sport after ACLR, they are at an increased risk of reinjury. Our study found that female soccer players after ACLR demonstrated increased knee abduction angles and knee adductor moments, both of which have been associated with an increased risk for primary ACL injury. As such, the altered frontal plane knee mechanics observed in this study may be related to the increased risk for reinjury observed in this population. Our results would suggest that rehabilitation programs after ACLR should include a focus on the
restoration of normal frontal plane knee mechanics before the return to sports participation. As the relationship between return-to-sport criteria and risk for reinjury is unknown, the current criteria need to be re-evaluated to determine their association with lower extremity biomechanics and risk for reinjury. Future studies are needed to investigate the underlying reasons for ACL reinjury.

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